Constraining the Lifetime of SO_2 in the Atmosphere of Venus from a 1D Climate-Chemistry Atmospheric Model

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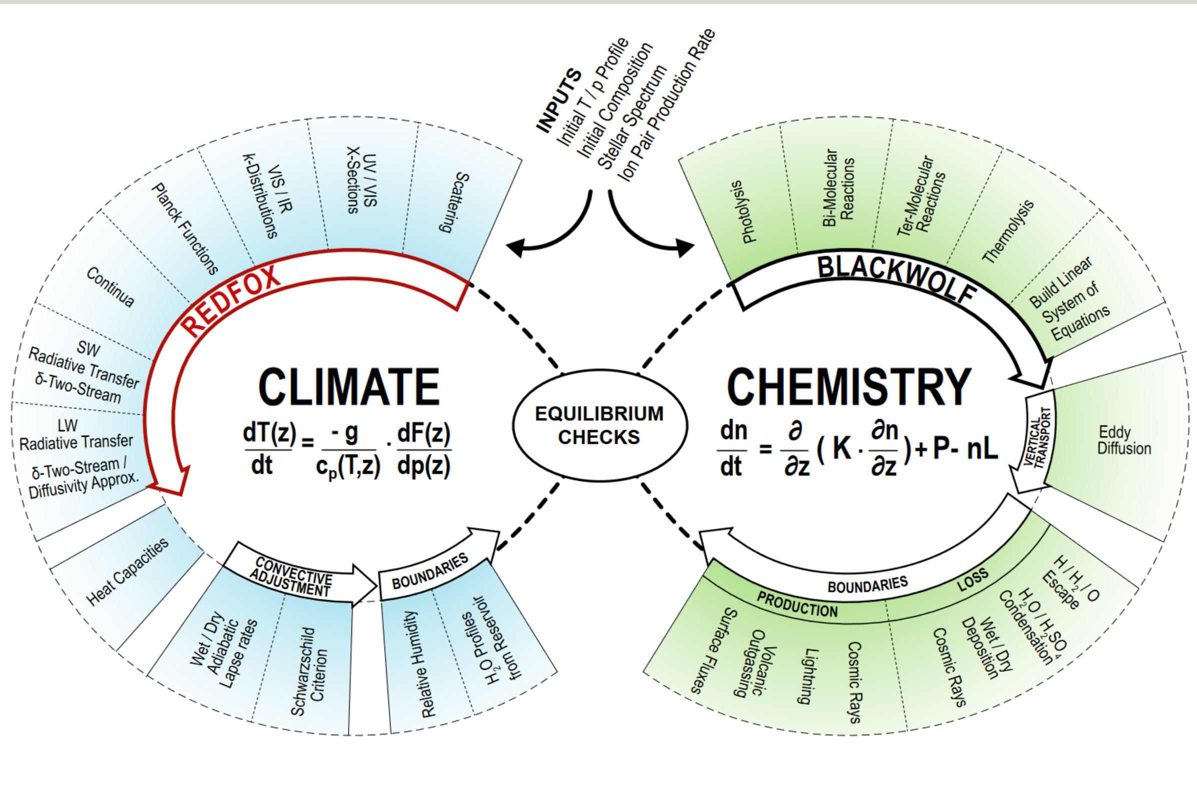
Introduction and Atmospheric Model, 1D-TERRA



1D-TERRA

The DLR's state-of-the-art atmospheric column model, 1D-TERRA [1,2], has been equipped with a dynamic, dry deposition velocity routine. Standard practice in atmospheric modelling is to fix the rate of deposition as a model boundary condition. For Venus, these rates are typically tuned to fit model outputs to observations as the surface-atmosphere interactions on Venus are not well constrained. In reality, uptake of trace gas species by surfaces can be highly sensitive to atmospheric temperatures, pressures, wind speeds, and much more. Our newly developed scheme enables the rate, determined by the *deposition velocity* of a species, of the 127 gas-phase species in our model to be estimated.

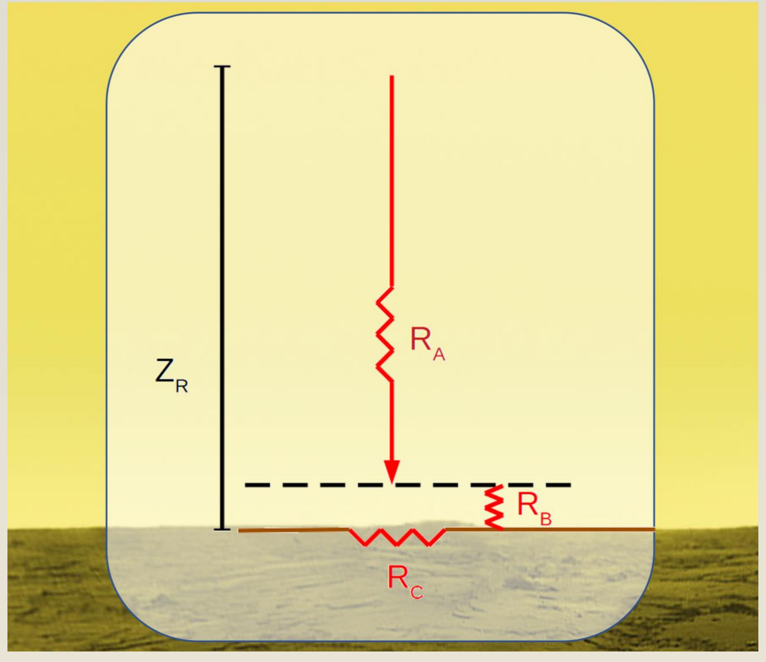
To validate this new submodule, we can compare the calculated *global mean* deposition velocities in an Earth simulation to those observed by measurements taken in the field.

Dry Deposition Velocity Parameterization

Loss of gas species to the surface is through *dry deposition*. The loss flux (molecules cm^{-2} s^{-1}) is found by multiplying the surface concentration (molecules cm^{-3}) by the species *dry deposition velocity* (cm s^{-1}).

$$F_{SO2} = [SO_2]_{Surf} \times v_{Dep,SO2}$$

$$v_{Dep} = (R_A + R_B + R_C)^{-1}$$



R_A : Aerodynamic Resistance

Resistance of a gas parcel at ref. height Z_r to reaching sub-laminar layer altitudes (0.01—1 cm)

R_B : Resistance to Molecular Diffusion

Resistance of individual trace gas species to transport via molecular diffusion to the planet surface.

R_C : Resistance to the Surface Layer

Resistance of gas-phase species to uptake to the surface via chemical reactions, physical uptake, adhesion etc. At present, the model uses the parameterization used in Earth GCM's for a bare rocky surface. Future work is required to introduce more complex reactivity parameterizations, such as specific weathering reactions.

R_A

R_A requires Monin-Obkuhnov Length (L), and surface friction velocity (u^*):

$$R_A = \int_{z_{0,q}}^{z_r} \phi_H \frac{dz}{z} \,/\, ku^*$$

$$L(u^*) = -\frac{u^{*3}\, T_S}{k\, g\, Q_{0,v}} \qquad u^*(L) = \frac{k\sqrt{u^2 + v^2 + w_*^2}}{\int_{z_{0,M}}^{z_R} \phi_M \frac{dz}{z}(L)}$$

Convergence routine (Newton-Raphson) developed to solve for correct u^* value.

Figure 1 colorbar shows value of F(u^*) for guesses of u^*_i for Earth's atmosphere for varying values of reference height, z_R. Convergence possible (no local minima).

- Solution u^* is insensitive to reference height
- Input parameters: mean wind speed at 10 m, surface roughness length ($z_{0,M}$)

Numerics of convergence function

$$F(u^*) = u^*(L) - L^{-1}(u^*)$$

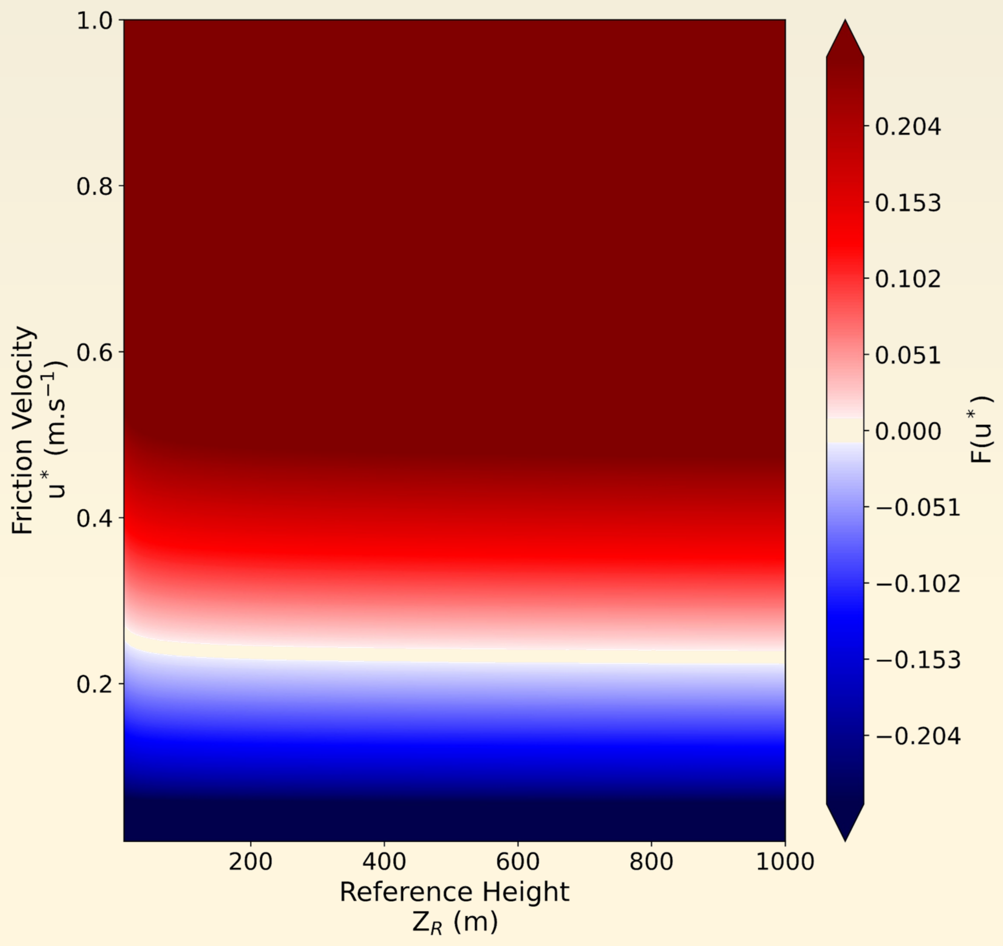


Fig 1: Proof of existence of global minimum enabling convergence scheme to find u^* value

R_B

$$R_{B,i} = 2\left(\frac{\nu}{\mathrm{Pr}\, D_{a,i}}\right)^{\frac{2}{3}} (ku^*)^{-1}$$

R_B is unique to each trace gas species, and is dependent on the molecular diffusion coefficient of the gas in the atmosphere, $D_{a,i}$, and the kinematic viscosity of the air, ν.

R_C

Surface resistance methodology from Kerweg et al 2006 [3] assuming a barren/desert surface.

$$R_C = \left(\frac{10^{-5} H_{Eff}}{R_{S,SO2}} + \frac{f_{0,i}}{500}\right)^{-1}$$

$$R_{S,SO2} = 225 - 85 \times \mathrm{MAX}(0, \frac{(40 - RH)}{40})$$

Parameters of the Venusian Surface

1D-TERRA model initialised with Venus inputs, and calculates atmospheric parameters at the near surface relevant to dry deposition scheme (Table below).

Wind speed magnitude at surface taken as 1.5 ms^{-1}, surface assumed to be barren rock (further work needed to study specific mineralogy impacts) with roughness length ($z_{0,M}$) 0.01 m. Prandtl number (Pr) is the ratio of momentum and thermal diffusivity of air.

Parameter	1D-TERRA Calculated Value
Pr	0.67
L (m)	-789.08
u^* (m s^{-1})	7.53x10^{-2}
R_A (s m^{-1})	186.76
$R_{B,SO2}$: $R_{C,SO2}$	585.00 : 1.00x10^4
$v_{Dep,SO2}$ (cm s^{-1})	9.23x10^{-3}

[1] Scheucher et al. 2020, ApJ 898 44, DOI: 10.3847/1538-4357/ab9084
[2] Wunderlich et al. 2020, ApJ 901 126, DOI: 10.3847/1538-4357/aba59c
[3] Kerweg et al. 2006, Atmos. Chem. Phys. 6, 4617—4632 , DOI: 10.5194/acp-6-4617-2006
[4]Svedhem et al. 2007, Nature 450, 629—632, DOI: 10.1038/nature06432

Preliminary Results

1D-TERRA is ran with a fixed surface vmr for CO_2 (0.965), SO_2 (100 ppm) [4], HCl (0.05 ppm) [4]. A converged run produces a deposition velocity for SO_2 of 9.23x10^{-3} cm s^{-1}. At 100 ppm, SO_2 surface number density is 8.72x10^{16} mol. cm^{-3}.

$$F_{SO2} = 8.05 \times 10^{14}\ \mathrm{mol.\,cm^{-2}s^{-1}} \equiv 11633\ \mathrm{Pg\ yr^{-1}}$$

The column lifetime due to surface uptake in our preliminary runs is found by taking the ratio of the SO_2 column (1.42x10^{23} mol. cm^{-2}) with the surface loss flux, yielding a deposition lifetime of τ_{SO2} = *5.59 years*.

To maintain the 1D-TERRA SO_2 column produced via the 100 ppm fixed surface value, an additional surface flux (most probably attributable to volcanism) is required. This value is calculated to be 2.16x10^{11} mol. cm^{-2} s^{-1}. Distributed equally across the surface, this yields a SO_2 flux of *3.12 Pg yr^{-1}*.

Future Work

- Sensitivity study for dry deposition input parameters.
- Include weathering rates of minerals on the surface.
- Study other volcanic species (HCl, CO_2, H_2S etc.) to assess potential outgassing ratios.
- Intensive validation for Earth runs to compliment the Venus applications.